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Experimental Study on Wood Material under Different Oxygen Concentration

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Abstract

The experiment of the non-piloted ignition of corrugated paper exposed to variable heat flux (the rate of heat flux γ=0.0556) and a series of oxygen concentration (20.9%, 18%, 16%, 15%) was carried out by adjusting the oxygen concentration and the output power of radiation source. The aim of the study is to analyze the effect of variable heat flux and oxygen concentration on ignition time, mass loss and mass loss rate. A numerical model was built to obtain the kinetic parameters under different oxygen concentration condition. The study results show that: under the same output power of radiant source condition, as the increase of oxygen concentration, the mass loss rate will increase, but the ignition time, the activation energy and the frequency factor will decrease.

Keywords: wood material; variable heat flux; oxygen concentration

Nomenclature

A	frequency factor (s^{-1})
c	oxygen concentration (%)
E	activation energy (kJ/mol)
R	gas constant (kJ/(mol·K))
t	ignition time of corrugated paper (s)
Δt	maximum difference of ignition time (s)
T	surface temperature of corrugated paper (℃)
Greek symbols	
α	percentage of weight loss at the time of t
β	rising rate of temperature (℃/s)
γ	rate of heat flux ($kJ/(m^2 \cdot s)$)

1. Introduction

Wood, a kind of combustible material, is widely used in many occasions. The combustion properties of which is a main topic studied by fire scientific research personnel. Toal, Silcock et al[1,2,3], Jamssems [4], Quintiere [5], and Spearpoint et al.[6] carried out many lighting and combustion experiments and theoretical work about wood[7], but these were mostly in the constant heat flux conditions. The happening of fire is an uncertain thing. In the actual fire process, the factors such as fire size, thermal radiation size and oxygen concentration of combustion process will make a great influence on the combustion.

Characteristics of materials: Generally speaking, the ignition of heat radiation is an important part in the fire process [8]. A lot of fire phenomenon shows that the thermal radiation is a major energy transfer mode in the spread process of fire. The

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material within a certain distance will be ignited by the heat generated by the thermal radiation. In addition, large amounts of oxygen will be consumed in the combustion process, in the meantime, the indoor space maybe in the closed state. If the fire burns in the closed condition, the indoor oxygen concentration will be sharply decline for the continuous combustion, and make the environment into lean oxygen state, so, the combustion will be go on in the lean oxygen conditions [9]. The change of oxygen concentration will affect the formation of carbon monoxide of the flue gas generated in the fire. The decline of oxygen concentration and the increase of carbon monoxide concentration will certainly have an effect on the breathing of the people in the fire and will affect the escape, but also will bring many dangers and inconveniences to the fire rescue. Therefore, in order to reduce the personnel casualties and property losses in the fire, it's necessary to study the combustion characteristic of material in different oxygen concentrations under the fire conditions. This study was based on the corrugated paper which is a common combustible wood material, and a series of experimental study were carried out on the fire test bench.

2. Reduced-Scale fire tests

The fire experimental table is showed in figure 1. The whole frame is made of stainless steel material and it has two folio glass doors, which connected by electronic balance, temperature measuring equipment, oxygen concentration analyzer, camera and computer and etc. The data information is recorded by electronic balance and temperature equipments as the sampling frequency of 0.1s each time, and the data is transferred into computer for later analysis.

Fig. 1. Experimental facility

There is no added ignition device in the test bench. The heat which transfers to the sample surface is mainly conducted by the top of the conical instrument in the form of thermal radiation. The distance between the thermal radiation source and the sample can be adjusted by lifting platform. The size of the material is 100 mm × 100 mm. The radiation heat flow used in this experiment is 40% of the total output.

The oxygen concentration ranged from 0 to 20.9% can be conducted by adjusting the nitrogen pressure and the air flow velocity. Four different oxygen concentrations were took in this experiment, as 20.9%, 18%, 16% and 15%. Under the experimental output power condition, the relation graph of thermal radiation intensity q and time was showed in figure 2. As can be seen from the graph, the relation graph of thermal radiation intensity and time appears as approximate linear relationship; therefore, to simplify the relationship, it can be treated as linear relationship in the treating processes. The slope of linear fitting curve is the heat flux rate of radiation source output power, which is recorded as γ , of which the unit is $\mathrm{kJ/(m^2 \cdot s)}$. The heat flux rate of this experiment is 0.0 556 $\mathrm{kJ/(m^2 \cdot s)}$.

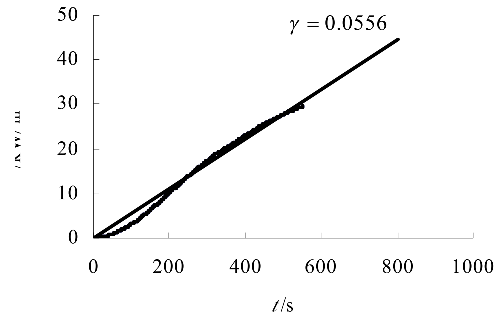


Fig. 2. Experimental and fitting curve

3. The experimental results and the analysis

In order to minimize the error, the experiment has been taken at least three times under each condition. According to the results, some other experiments will be continued if remarkable difference appears. Because the related parameters of the experimental process in small size is easier to control, therefore, in this experiment, small size fire experiment table is used to simulate the combustion characteristic of indoor wood material under lean oxygen condition in closed space.

3.1. Ignition time

Ignition is an important phenomenon in the fire process. The ignition time is an important parameter to judge the combustion characteristic of the material, and it is also an important index to evaluate the early fire risk. In the process of the study to the influence of the fire evacuation and the building structure, ignition time can directly reflect the fire risk of material. In this experiment, ignition time is defined as the time from the heating to the material at the beginning to naked light appeared on the material [8]. The ignition time of corrugated paper under different oxygen concentration in the experiment is showed in table 1. It can be seen from the table that under a certain heat flow condition, the ignition time increases along with the reduction of the oxygen concentration. In the experiment, the ignition time is 297 s at the oxygen concentration of 20.9%, the ignition time is 378 s at the oxygen concentration of 15%. In this experiment, to the four different oxygen concentrations, the first three ignition time present an approximate linear relationship, of which the related coefficient is 0.9 827. When oxygen concentration reduces from 16% to 15%, the ignition time will increase sharply. This phenomenon indicates that this oxygen concentration has a great influence to the ignition, and at this oxygen concentration, it is more difficult to light the sample. Therefore, it can be inferred that if the oxygen concentration is under 15%, the sample will be more difficult or even cannot be lighted at all. Under these conditions of the experiment, the ignition time is between 200 s~400 s, and the maximum time is 81 s.

Table.1. Ignition time

γ /(kW/(m^2 • s))	c /%	t /s	Δt /s
0.0 556	20.9	297	81
	18	318	
	16	341	
	15	378	

3.2. Mass loss and mass loss rate

The mass loss rate is an important factor, which can influent the heat release rate in the process of thermal decomposition. By the study of mass loss, we can get a new insight into the process of thermal decomposition. The curve of mass loss in this paper is showed in figure 3. It can be seen that it has certain similarity to changing trend of the mass loss curve under each oxygen concentration condition. At the beginning of the experiment, due to the weak heat flux, little heat is radiated to the surface of the sample. Therefore, mass loss reduces slowly along with time, and appears smooth and steady. With the increase of heat flux and heating time, the temperature of the sample surface gradually increase, and meanwhile, it accelerates the velocity of thermal decomposition of the material. At the about 270 s, mass reduces quickly, and the turning point appears at the curve, and sample is lit. It can be seen in this curve that at the stage of fast thermal decomposition and combustion, with the decrease of the oxygen concentration, mass loss curves show offset upward trend. The curves appear smooth movement again at the end of the burning. Although lean oxygen concentration needs longer ignition time, the curves of mass loss seem similarly, rather than a longer stable stage. This shows that, when heated, thermal radiation also has certain effect on mass loss. Although the environment oxygen concentration is not enough to light the sample, with the long time heating, the heat radiated to the surface of sample accumulates, and make it accelerate thermal decomposition, consequently, mass also reduce at that time.

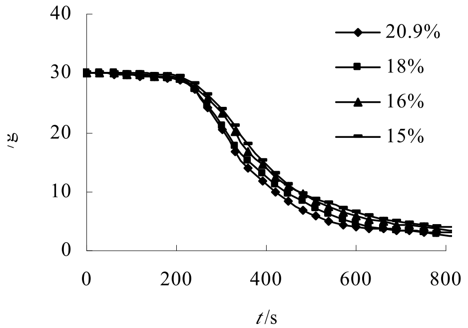


Fig. 3. The curve of mass loss

From the figure 3, before the time 150 s and after the time 450 s under the four conditions, mass changes only a little. So, when comparing the mass loss rate, these two parts can be ignored, and the time between 150 s and 450 s is chosen, as shown in figure 4. It can be seen from the figure that the peak of mass loss rate increases with the rise of oxygen concentration, and the occurrence time is delayed in turn along with the oxygen concentration. Under the set heat flux condition of the experiment, it can be obtained that the maximum peak is about 4 g/s, the minimum is about 2.9 g/s. Therefore, it is known that under a certain heat flux condition, with the oxygen concentration increases, accordingly, ignition time of the material decreases. In addition to this, the sample burns more rapidly and the mass decreases faster.

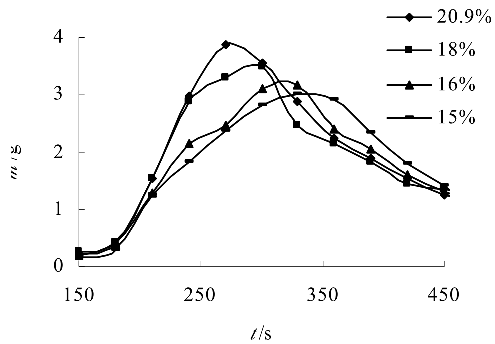


Fig. 4. The curve of mass loss rate

4. The pyrolysis kinetics parameter of wood material under different oxygen concentration

The physical thermal decomposition model [10] is showed in figure 5.

- The heat inducted refers to the heat of upper layer, and export heat refers to the heat of down layer;
- It is assumed that volatile matter leave the surface of the material immediately, and do not consider the effect of mass transfer resistance, so that the process of mass transfer and heat transfer of energy can be simplified;
- The surface shrinkage is not considered, and it is considered that the solid volume remains constant;

- The single step first order Arrhenius formula is chosen in the reaction;
- The reaction between volatile gas and thermal carbon layer is neglected.

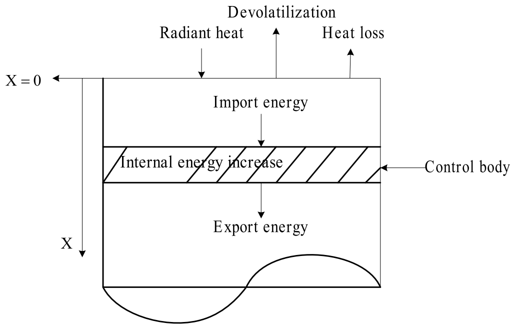


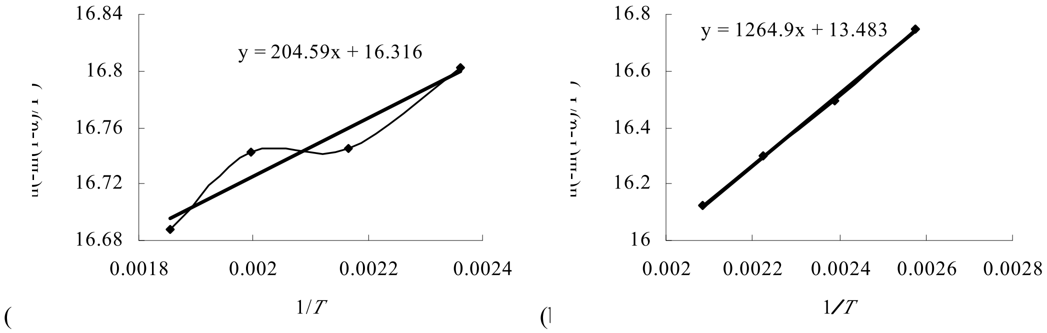
Fig. 5. Physical thermal decomposition model

The Coats-Redfern integral method [11] is used in this paper. Through the approximate derivation to the temperature integral, Coats and Redfern pushed out the approximate integral type equation showed as equation (1). Because $2RT/E \ll 1$, due to the equation (1), it can be seen that to the right form of $g(\alpha)$, the relationship between $\ln\left(g(\alpha)/T^2\right)$ to 1/T is a straight line with a slope as $-E/R$, frequency factor A is intercept. Whether the relationship presents linear is the standard to judge $g(\alpha)$ is right or not. To the right form of $g(\alpha)$, the activation E and frequency factor A can be respectively obtained from the slope and intercept.

The relationships between key parameters and oxygen concentration are studied in this paper at three oxygen concentration as 18%, 16%, 15%. The rising rate of temperature can be obtained from slope of temperature curve.

$$\ln\left(\frac{g(\alpha)}{T^2}\right) = \ln\left(\frac{AR}{\beta E}\left(1-\frac{2RT}{E}\right)\right) - \frac{E}{RT} \tag{1}$$

Figure 6 is the curve of $-\ln(-\ln(1-\alpha)/T^2) \sim 1/T$ at first-order kinetics under different oxygen concentration. The followed three graphs in (a), (b) and (c) are the oxygen concentrations at 18%, 16%, and 15%. It can be seen that the curves appear approximate linear relationship. This phenomenon shows that the first-order reaction model is correct, and it coincides with the theoretical prediction. Straight line is the relevant fitting curve. When the slope, intercept and the obtained β are put in the equation $\ln\left(g(\alpha)/T^2\right) = \ln\left(AR/\beta E\right) - E/RT$, the two key parameter as activation energy E and frequency factor A can be get. Table 2 shows the combustion kinetics parameters under the conditions of different oxygen concentration. The relationship between activation energy E and frequency factor A is simply discussed in this paper. It can be seen from the data in that with oxygen concentration decreases, activation energy E and frequency factor A increase, and it is also be obtained that oxygen concentration and activation energy and frequency factor appear approximate inverse proportion.



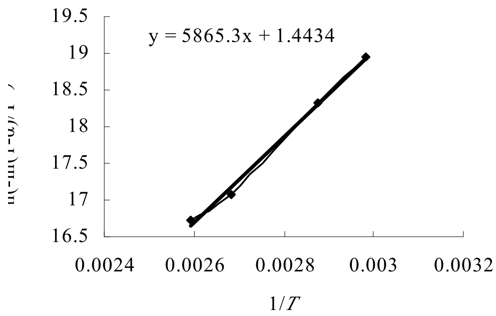


Fig. 6. The curves of –ln(-ln(1- α)/T^2)~1/T

Table 2. Key parameter

c /%	*E* /(kJ/mol)	*A* /s^{-1}
18	1.70	3.25E-05
16	10.51	0.0027
15	48.74	866.97

5. Conclusion

To study the fire characteristics of corrugated paper under different oxygen concentrations, a combustion characteristic test bench is built. By studying the relationship between different oxygen concentrations, activation energy *E* and frequency factor *A* of the key parameter, the following conclusions can be drawn:

- The change of oxygen concentration has a certain effect on ignition time and mass loss of the sample. With the reduction of oxygen concentration, the retardation phenomenon will occurs to the ignition time. The lower oxygen concentration, the longer ignition time is needed. The measured ignition time are between 200 s ~400 s under the four conditions set in the experiment;
- The peak of mass loss rate decreases along with the reduction of oxygen concentration. Before the peak arrives, the higher oxygen concentration, the greater the mass loss rate;
- Through the solution of the dynamic equation, it can be found that the first-order reaction kinetics fits for combustion of corrugated paper under different oxygen conditions;
- The activation energy and frequency factor increase along with the reduction of oxygen concentration. The increase of activation energy and frequency factor appears approximate inverse relationship.

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